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Review

A comprehensive review on vibration based micro power generators using electromagnetic and piezoelectric transducer mechanisms

Abu Raihan Mohammad Siddique, Shohel Mahmud *, Bill Van Heyst

School of Engineering, University of Guelph, Ontario, Canada

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ABSTRACT

The area of micro power generation has developed significantly over the last two decades in the field of microelectromechanical systems, self-powered wireless sensor nodes, and mobile platforms. Battery is the main power source of such systems but it has some limitations which include finite life time, periodic replacement, and environmental pollutions. Therefore, electrochemical battery system is not a suitable fit for wireless self-powered electronic industry. Energy harvesting through renewable energy such as mechanical vibration can be an attractive alternative solution to replace or widen the lifespan of the traditional battery system. A good number of researches have been conducted on vibration based micro power generation to support the microelectromechanical systems. Electromagnetic, piezoelectric, and electrostatic transducers are used to convert kinetic energy (i.e., mechanical vibration) into electrical energy. A comprehensive literature review has been presented on vibration based micro power generation using two most common transducer mechanisms: electromagnetic and piezoelectric transduction systems.

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Contents

1. Introduction . . . 729
2. Micro power generators . . . 729
   2.1. Vibration based MPG . . . 729
   2.2. Different types of VMPGs . . . 730
      2.2.1. Electromagnetic VMPGs . . . 730
      2.2.2. Piezoelectric VMPGs . . . 730
      2.2.3. Electrostatic VMPGs . . . 731
   2.3. Applications of VMPGs . . . 731
3. Literature review . . . 731
   3.1. Electromagnetic VMPGs . . . 731
      3.1.1. Using rectangular shaped cantilever . . . 731
      3.1.2. Using different shapes of cantilever . . . 734
      3.1.3. Using cylinder shaped structure . . . 736
      3.1.4. Using power conditioning circuit . . . 737
   3.2. Piezoelectric VMPGs . . . 737
      3.2.1. Using different piezoelectric materials . . . 737
      3.2.2. Using different geometry of PZT cantilever beams . . . 741
   3.3. Hybrid VMPGs . . . 742
4. Conclusion . . . 744
   References . . . 744

* Corresponding author.
E-mail address: smahmud@uoguelph.ca (S. Mahmud).

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1. Introduction

Over the last two decades, miniaturizing the transducer systems is one of the technological advancements in the microelectromechanical systems (MEMS) [1]. Therefore, the power consumption has been made in the order of mW to μW scale for MEMS devices [2]. This effort has reviled a new and attractive research area which is one of the suitable alternatives to replace the traditional energy resources (e.g., fossil fuels) and store this energy in a convenient way rather than using battery system [3]. Conventional batteries have a limited life time [4], need regular replacement, labor cost, and also have hazardous environmental impact (e.g., it releases chemical substances to the environment) [5]. Recently, researchers are very much concerned about the increasing global warming [6] because of using conventional fossil fuels [7] and electrochemical batteries [8]. Researchers have been working on various alternative renewable energy resources like solar, ocean wave, rain, sound, wind, acoustics, and thermal vibration [9]. These sources are clean, renewable as well as have tentatively infinite lifetime compared to batteries [10]. Among these sources solar, ocean wave, sound, and wind energy have already been massively used in industrial, commercial as well as residential area as a power source which has a huge initial setup cost and requires arrangements [11]. Hence, researchers have been trying to propose some energy sources which are unexplored verily yet such as generating electrical energy from kinetic energy and thermal gradient for modern MEMS industry [12].

Providing green and efficient renewable energy is a challenge for microelectronic equipment that requires milli to micro level energy for operation [13]. Vibration based micro power generator (VMPG) is one of the leading research fields for engineers for developing an energy efficient micro generation system for MEMS devices [14]. With the omnipresent availability of mechanical vibration energy, VMPG can be a suitable alternative energy source for self-powered wireless sensor network (WSN) [15] and mobile electronic platforms [16]. A transducer is required in order to convert the mechanical vibration energy into electrical energy. Three common transduction mechanisms: electromagnetic, piezoelectric, and electrostatic, are considered to be the most promising for VMPGs.

The objective of this research article is to represent a comprehensive survey of the rapid development in the area of VMPGs using electromagnetic and piezoelectric transducer mechanisms. In this review paper, hybrid micro power generators (e.g., electromagnetic with piezoelectric or electromagnetic with thermoelectric or any combination of vibration based energy source with other energy source) have also been presented. A summary of the literature review has been illustrated in a tabular form in the review section starting from 1996 to date.

2. Micro power generators

Micro power generators (MPGs) refer to the generators that are small in size (milli (m) to micro (μ) range) and use available surrounding energy sources to convert into electrical energy. The surrounding environment is a bank of different types of energy sources which can be trapped for harvesting and converting into electrical energy. Table 1 shows some natural energy sources that can be used for harvesting energy by MPGs.

2.1. Vibration based MPG

Recently, vibration, which is one of the forms of kinetic energy, is widely used by MPGs to harvest electrical energy [18]. VMPG can be defined as harvesting the available mechanical vibration from the surroundings and converting it into electrical energy. Vibration based energy sources are available in our surroundings: different types of commercial and industrial machines, vehicles, buildings, various structures (bridges, railways), household appliances, and human body movements. Table 2 represents the magnitude of vibration sources measured with respect to frequency and acceleration of the fundamental vibration.

Table 1
Energy sources available in the surrounding for harvesting electricity [17].

Main sources	Type of sources
Environment	Solar, wind, tide, temperature gradient, acoustic wave, sound, thundering, radioactive materials
Human body	Blood pressure, body temperature, walking, running, arm, leg, and finger motion, breathing
Vehicles	Automobiles, aircraft, trains, turbines, tires, ships
Structure	Building, bridges, roads, MEMS, control switch
Industrial	Motors, generators, compressors, fans, pumps, switch-gates

Table 2
Acceleration and peak frequency of different sources [19].

Vibration based energy sources	Acceleration (m/s^2)	Peak frequency (Hz)
Human walking	0.4	2
Passenger automobile engine	12	200
Base of 3-axis machine tool	10	70
After closing the door	3	125
Blender machine	6.4	121
Washing and drying machine	3.5	121
Instrumental panel of car	3	13
HVAC vents in commercial buildings	0.2–1.5	60
Microwave oven	2.5	121
Windows beside busy street	0.7	100
Footbridge	–	0.9–1

VMPG is usually designed in such a way so that the natural frequency matches with the excitation frequency. VMPGs consist of a mechanical oscillator system, energy conversion device i.e., a transducer, and power management circuit. The schematic diagram of vibration based micro power generation system is illustrated in Fig. 1.

The electromechanical system consists of two main systems. One is mechanical (mass-spring-damper) system and the other one is electrical system (the load resistance, inductance and internal resistance of the coil) as shown in Fig. 2.

The system showed in Fig. 2(a) consists of a proof mass (m, kg) which is attached to one end of the spring. This spring (k is the spring constant, N/m) is attached to the system which will vibrate due to the external vibration. The dashpot has a total damping of b_t which consists of electrical and mechanical damping represented by b_m and b_e, respectively. When the system is subjected to a vibration the mass moves with the generating housing where $y(t)$ and $x(t)$ are the displacement of frame and relative displacement of mass and frame, respectively. The electromechanical system presented in Fig. 2(b) is used to get the transfer function. It includes electromagnetic transducer system to convert the vibrational energy into electrical energy. Here, L is the coil inductance (H); R_C and R_L are the internal coil resistance (Ω) and the load resistance (Ω), respectively; and V is the load voltage (V). The power (P, W) can be calculated from spring-mass system which is dissipated from electrical damping given by [11].

$$P = \frac{Y_{\max}^2 \zeta_e m \omega_e^3 \left(\frac{\omega_e}{\omega_n}\right)^3}{\left(1 - \left(\frac{\omega_e}{\omega_n}\right)^2\right)^2 + \left(\frac{2\zeta_t \omega_e}{\omega_n}\right)^2} \quad (1)$$

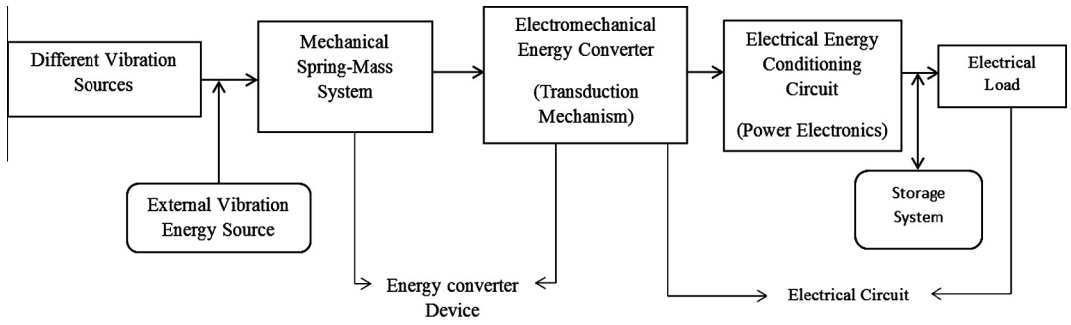


Fig. 1. Schematic diagram of vibration-based energy harvesting system.

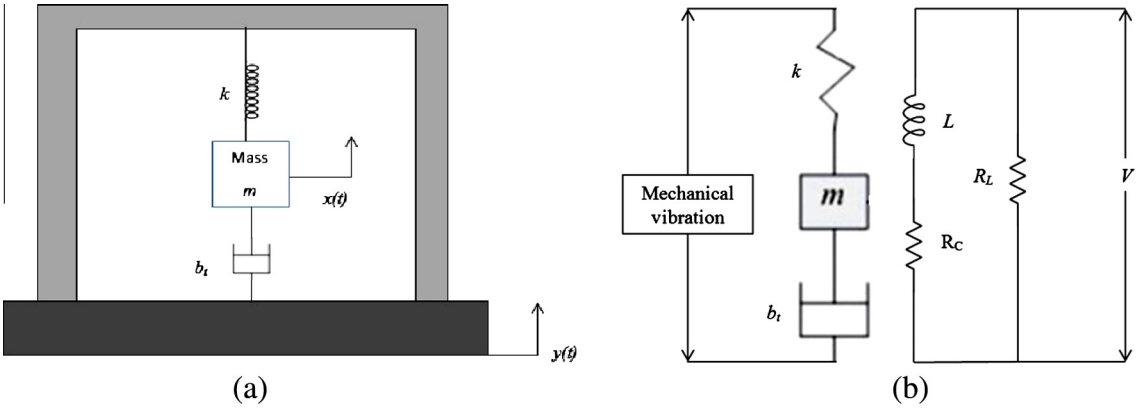


Fig. 2. (a) Spring-mass system for vibration based MPG model and (b) electromechanical representation of the system.

Table 3
Characteristics of different transduction methods [19,27,28].

Type	Practical maximum energy storage density (mJ/cm^3)	Advantages	Disadvantages
Piezoelectric	35.4	Simple structure, easy to fabricate, high output voltage levels (>5 V), easy to voltage rectifying, large piezoelectric coefficient and dielectric constant	Low output current (nA to μA), high output impedance (>100 kΩ)
Electromagnetic	24.8	A number of positions or designs are available for device architecture, relatively low output impedance, high output current (μA to mA), tuning is possible to low, medium, high vibration levels	Low output voltage (typically <1 V), difficult to rectify the voltage, too small vibration amplitudes, low electromechanical coupling coefficient
Electrostatic	4	Very high output voltage (>100 V), easy to voltage rectifying and frequency tuning	Switching circuit required for operation, requires voltage source for initial charge, high resonant frequency, high output impedance, low output current

2.2. Different types of VMPGs

A transducer mechanism must be introduced to convert the vibration energy into electrical energy. There are different types of transduction mechanism such as electromagnetic, piezoelectric, electrostatic, and combination of any of two i.e., hybrid. But among these, electromagnetic and piezoelectric are mostly used in VMPG systems.

2.2.1. Electromagnetic VMPGs

According to the Faraday's law of electromagnetic induction, electromagnetic force arises for the relative movement of magnetic field and electric current carrying conductor. In electromagnetic VMPGs, this basic principal is followed to generate the electrical energy from mechanical energy. Vibration is used as a means of mechanical energy to vibrate the coil to the magnetic field or vice versa. Therefore, it generates electromotive force (EMF) which causes a current flow in the load circuit.

2.2.2. Piezoelectric VMPGs

Piezoelectric generators are used to produce voltage using piezoelectric materials which generate electrical charges when it experiences a mechanically stressed. In piezoelectric transducers, kinetic energy i.e., vibrations is used to produce potential difference between piezoelectric materials thereby generating voltage. In 1880, Curie and Curie were the first to introduce the piezoelectric effect and they observed that if certain piezoelectric material (e.g., crystal) was subjected to stress, they became electrically polarized. Various forms of piezoelectric materials are available including: aluminum nitride (AlN) [20], cadmium sulfide (CdS),

gallium arsenide (GaAs), barium sodium niobate [21], lead zirconate titanate (PZT) [22], natural crystal (e.g., lead titanate-$PbTiO_3$, quartz-SiO_2), piezo ceramic materials and powders [23], synthetic ceramics (e.g., $BaTiO_3$, ZnO, ZnS) [24], sputtered zinc oxide, and polymeric materials (PVDF) [25].

2.2.3. Electrostatic VMPGs

Electrostatic transducer is another type of transformation process of translating mechanical energy into electrical energy. This conversion process is done by the electric forces and work is done using the relative movement of isolated capacitor plates which are already electrically charged. The work done against the force between two electrically charged plates delivers static electricity. According to the movements of the plate, battery-based electrostatic transducers are categorized as: plane overlap, in-plane closing gap, and out-of-plane closing gap [26]. Table 3 presents the advantages and disadvantages with average energy storage density of these three different transduction mechanisms.

Therefore, most of the researchers consider piezoelectric and electromagnetic transduction mechanisms to be the best ones suitable for vibration based micro power generation because of their advantages over electrostatic mechanism.

2.3. Applications of VMPGs

VMPG is a relatively new technology used in MEMS industries. The use of VMPG is growing faster for newer and newer applications. The main objective of the vibration based energy harvester is to provide small power to those devices which require milli to micro power. VMPGs have potential to replace small scale battery system or to increase the life time of the battery. Some applications include advanced wireless data transmission protocol Zigbee system [29] and picoradio system [30,31], aerospace and deep sea applications [32], mining field [33], nuclear power station (e.g., sensors inside the reactor) [34], implantable bio-sensing application (i.e., pace makers and cochlear implants) [35], controlling industrial monitoring systems (e.g., different sensors which are located in dark and dirty remote environments) [36], controlling and monitoring the automobile sensors (e.g., vehicles speed sensor, air flow sensor, cruise control, engine heat sensor, etc.) and recharge small batteries using potential energy of engine vibrations [37], wireless communication systems (e.g., IEEE 801.15.4 wireless sensor protocol) [38], sensors in institutional and commercial buildings [39], tracking the movement of the livestock as well as their health condition [40], sensors in active end of service life indicator (AESLI) [41], low powered communication devices (e.g., pagers, two way communicators, etc.) from human heel strike [42], wireless sensor networks (e.g., WiseNET introduced by Swiss Centre for Electronics and Micro technology) [43].

3. Literature review

VMPGs are becoming attractive gradually because of their generating mechanism without any turbine or engine (prime mover). The research on vibration based energy harvesting has started since the 1980s. Possibly the first energy generating system was made by Hausler and Stein in 1984 [44]. As a consequence in the late 1990s, the first energy-harvesting devices were fabricated by the Media Lab at MIT (e.g. using three different vibration energy generators in shoes [45] and using piezoceramic converter in shoes [46]). After that Williams and Yates introduced the main concept of vibration based energy harvesting in 1996 [11]. A state of the art review on vibration based electromagnetic, piezoelectric, and hybrid power generators has been presented in this section.

3.1. Electromagnetic VMPGs

Electromagnetic is the widely used transducer technique in energy conversion process of VMPGs. A beam is used to vibrate along with coil or magnet and according to the Faraday's law it generates electrical energy. Different shapes of cantilever beam (e.g., rectangular shape, cylindrical shape, and other different shapes) and different magnets with different coil size are being used for conversion process.

3.1.1. Using rectangular shaped cantilever

As early as 1996, William and Yates [11] analytically investigated an electromagnetic vibration based energy harvester having a size of $5 \times 5 \times 1\ mm^3$. Silicon diaphragm was used for analytical calculation. It was noted that power output is directly proportional to the cube of the vibration frequency. The power output of their generator is 1 μW and 0.1 mW at 70 Hz and at 330 Hz, respectively, with vibrating amplitude of 50 μm from their designed prototype.

A similar kind of approach of energy harvesting from mechanical vibration was described theoretically and experimentally by El-hami et al. [47]. Permanent magnet (e.g., samarium–cobalt, neo dymium–iron–boron (NdFeB)) was used in C-shaped core. The size of their prototype is 240 mm^3 with a power output of 0.53 mW at 322 Hz. The research of El-hami was further investigated by Glynne-Jones et al. [48] who designed two prototypes with NdFeB magnets. Prototype A consists of two magnets having a size of 0.84 cm^3, whereas prototype B consists of four magnets having a size of 3.15 cm^3 (see Fig. 3). The power output of prototype A and B are 37 μW and 157 μW, respectively.

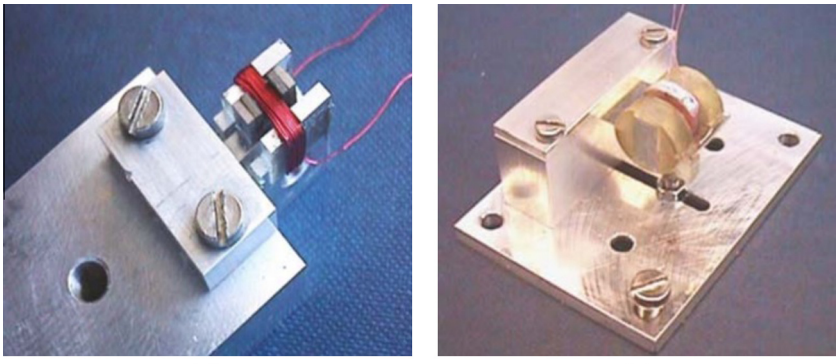


Fig. 3. Micro generator (a) prototype A, (b) prototype B developed by Glynne-Jones et al. [48].

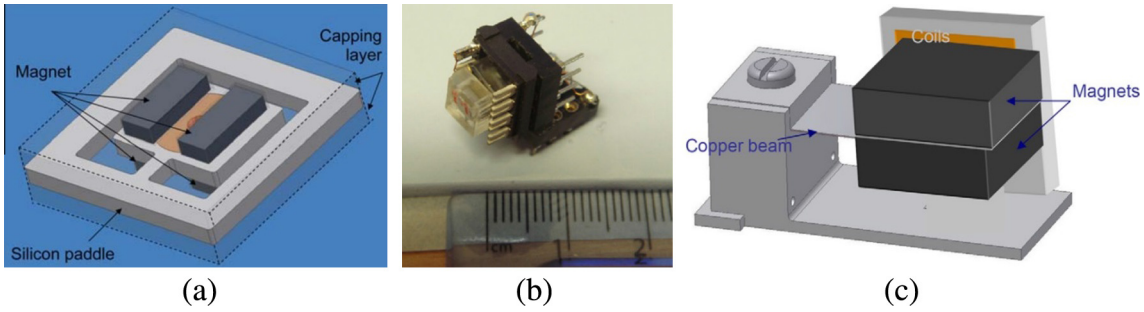


Fig. 4. Silicon micromachining technology based generator developed by (a) Koukharenko et al. [52], (b) and (c) Kulkarni et al. [54].

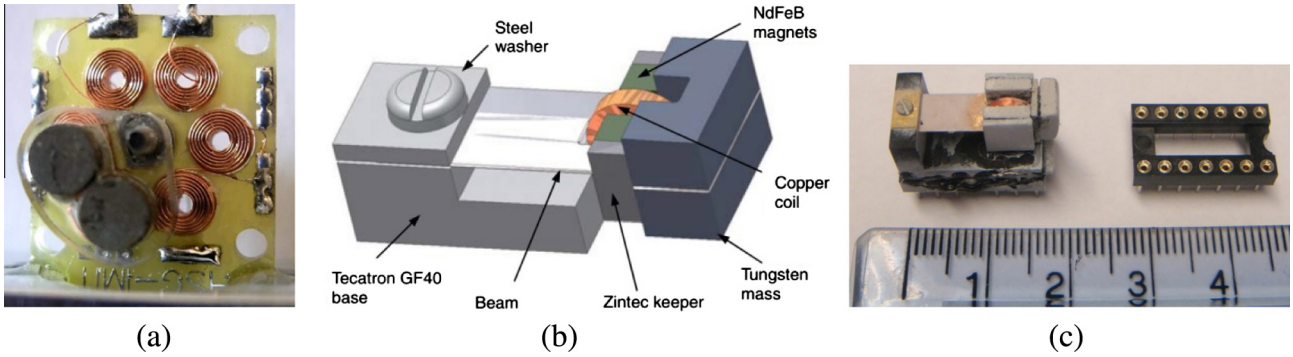


Fig. 5. (a) Non-resonant vibration based transducer developed by Spreemann et al. [56]. (b) Schematic diagram of micro generator designed by Beeby et al. [58] and (c) tunable micro generator developed by Zhu et al. [15].

Mizuno and Chetwynd [49] also used permanent magnet NdFeB with an array of cantilever beams to increase the efficiency of the generator. The size of the beam is $500 \times 100 \times 20\ \mu m^3$. Researchers reported that their designed micro generator can generate 1.4 mV and 6 nW at 58 kHz with an amplitude of 100 nm. Kulah and Najafi [50] also conducted research on the array of cantilever beam for designing a micro scale generator. Frequency up-conversion technique was used to boost up the low frequency. Their prototype generates 2.5 μW and 150 mV at 100 kHz resonant frequency.

A detailed description of design, modeling, and fabrication process of vibration based electromagnetic generator was explained by Beeby et al. [51]. The simulated results show that voltage output is 0.38 V at 6.4 kHz with a maximum amplitude of 0.14 mm. Research work of Beeby et al. [51] was further extended by Koukharenko et al. [52] and Kulkarni et al. [53,54]. Using numerical and experimental techniques, Koukharenko et al. [52] presented a micro energy harvester. Silicon micromachining technology was used to fabricate the prototype. ANSYS was used for optimizing the design of the prototype. The size of prototype is 100 mm^3 (see Fig. 4(a)). Simulated results show that power and voltage output are 0.11 mW and 0.7 V at 1.6 kHz, and 3.35 mW and 4.15 V at 9.5 kHz, respectively, with an amplitude of 240 μm. Besides, Kulkarni et al. [53] designed a similar micro generator using the same technology, having a size of 30 mm^3. The voltage and power output from the prototype are 55 mV and 70 μW at 7.4 kHz with an acceleration of 1.1 m s^{-2}. In a later research, Kulkarni et al. [54] developed three different prototypes to improve the design of the previous study. Prototype A (see Fig. 4(b)), prototype B (see Fig. 4(b)), and prototype C (see Fig. 4(c)) generate 148 nW, 23 nW, and 586 nW at 8.08 kHz, 9.83 kHz, and 60 Hz, respectively. It is reported that the size of prototype B is 0.1 cm^3, which was the smallest generator using silicon micromachining technology that time.

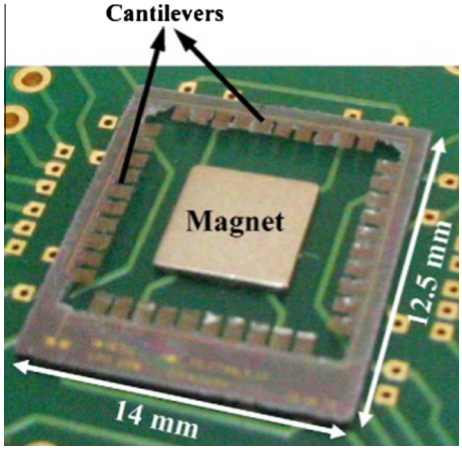


Fig. 6. An array of 40 cantilevers was used to develop a vibration based power generator by Sari et al. [59].

Pérez-Rodríguez et al. [55] also used ANSYS to design and optimize the generating power from electromagnetic VMPG based on Si technology. Fixed coil with moveable magnet was used on a vibrating membrane for their developed VMPG. The designed converter can generate up to 385 μW at 120 Hz with an amplitude of 2.5 m s^{-2}. Besides, Spreemann et al. [56] described a new frequency conversion technique (non-resonant technique) with some advantages: it can convert low frequency; it has the ability to convert high and low frequency simultaneously; and it has a wide frequency range. The size of their prototype is 1 cm^3 as shown in Fig. 5(a). Their proposed generator has a power output of 0.4–3 mW at 30 Hz to 80 Hz.

Additionally, to improve the conversion efficiency (magnetic energy into electrical energy) of the generator, Torah et al. [57]

developed a novel cantilever beam based electromagnetic energy harvester. The size of their designed generator is 150 mm^3 using NdFeB magnet. The measured power output of the prototype is 17.8 μW at 60 Hz having a load resistance of 150 Ω. The research was continued by Beeby et al. [58] who optimized the coil properties as well as magnet size to improve the power generation of system. The dimension of the generator is 0.15 cm^3 (see Fig. 5(b)). Maximum power output of their modified generator is 46 μW at 52 Hz having a load resistance of 4 kΩ. It was measured that 30% of the converted power can be delivered to the load from their developed generator. In a similar research, Zhu et al. [15] continued the work of Beeby et al. [58] where Zhu et al. [15] presented a frequency tunable generator (see Fig. 5(c)). Axial tensile force was applied to the generator to tune the frequency. It was observed that their designed generator can be tuned in the frequency ranging from 67.6 to 98 Hz with power output between 61.6 and 156.6 μW.

In a later study, Sari et al. [59] investigated to broaden the frequency range of the VMPG using different lengths of cantilevers array. Cantilevers are connected in series. NdFeB was used in their designed generator having a size of 14 × 12.5 × 8 mm^3 (see Fig. 6). Both numerical simulation and experiments were conducted to validate their design. A detailed explanation of the fabrication process was presented using five masks with SiO_2 substrate. The voltage and power output of the prototype were 10 mV and 0.4 μW, respectively, over a frequency range from 3.5 to 4.5 kHz. In a subsequent study, Sari et al. [3] described similar fabrication process with mathematical modeling. Optimization of the size of generator was also included in their new study with an array of 20 cantilevers. Their modified generator size is 9.5 × 8 × 6 mm^3 having a power output of 56 pW per cantilever at 3.4 kHz. In order to improve the efficiency, frequency up-conversion mechanism was used by Sari et al. [60] in their modified design. The size of the generator is 8.5 × 7 × 2.5 mm^3 having a power output of 0.25 nW per cantilever at 50–200 Hz.

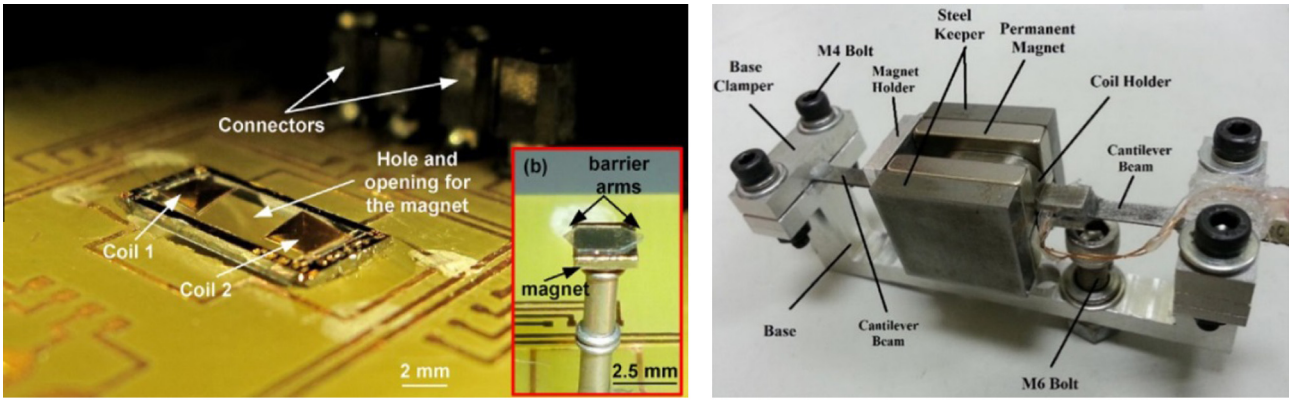
In order to improve the generated power, Soilman et al. [61] investigated two important parameters, i.e., the coil configuration and electrical damping coefficient of their developed prototype. A maximum power of 190 μW was obtained at 2 Ω load resistance. It is reported that the maximum electrical efficiency becomes 94% if the number of coil is infinity.

Zorlu and Külah [62] also used frequency up-conversion technique. Non resonant vibration (e.g., using low frequency with low vibration amplitude) based energy harvester using NdFeB was proposed. The dimension of the generator is 2.5 × 2.5 × 0.5 mm^3. An optimum rms voltage and power of 2.1 mV and 18.5 nW, respectively, were obtained under 10 Hz. The fabricated prototype was attached to the Printed circuit board (PCB) for harvesting power (see Fig. 7(a)). Besides, using frequency up-conversion technique, Zorlu et al. [63] proposed a novel electromagnetic vibrator structure having single diaphragm with single coil instead of a number of coils. Their designed prototype was the modified version of Sari et al. [3]. The size of the prototype is 10.4 × 8.8 × 5 mm^3. The prototype has a maximum voltage and a power output of 12–18 mV and 3.6–8.1 nW at 5–10 Hz with a vibration amplitude of 3 mm. It was reported that increasing the number coil turns as well as effective coil area improves the performance of the micro energy harvester.

Pashaei and Bahrami [64] also described frequency up-conversion method in order to improve the generated power from low frequency based electromagnetic micro generator. To increase the ambient low frequency, planer spring with two magnets and four cantilever beams were used to construct the structure of the generator. The voltage and power output from their developed prototype are 67.4 mV and 46.6 μW, respectively, at 75 Hz (after up-conversion frequency becomes 5.9 kHz). Another method to improve the frequency range of the energy harvester is to use double resonant method which allows both magnets and coils to vibrate at an additive phase angle. Ooia and Gilbert [65] used double resonant technique to widen the frequency band of their designed generator (see Fig 7(b)). MATAB was used to simulate the numerical model analysis. From experimental results, it was obtained that their prototype has a voltage of 259.5 mV at 21.3 Hz with 0.8 m s^{-2} acceleration.

In another study, Sato et al. [66] presented an analytical method to describe the motion, circuit, and Maxwell's equations using the coupled analysis technique to develop the VMPG. From the coupled analysis method it was noticed that vibration based energy harvester has linear and chaotic oscillations at a large coil radius. In a subsequent study, Sato and Igarashi [67] developed a prototype to validate their previous research. Their designed generator has a power output of 0.1 mW at 30 Hz from numerical and experiment tests.

A different type of material (FR4) was used to fabricate a nonlinear bi-stable electromagnetic transducer by Podder et al. [68]. A detailed explanation of design, modeling, and fabrication was presented to describe their prototype and validate their results. Two oppositely oriented NdFeB magnets were used for introducing the bi-stable state (see Fig. 8). Experimental results show that the generator harvests 22 μW at 35 Hz with a resistive load of



(a) (b)

Fig. 7. (a) Picture of micro energy generator chip designed by Zorlu and Külah [62] attached to the PCB with NdFeB magnet and barrier arms. (b) Dual resonator generator developed by Ooia, and Gilbert [65].

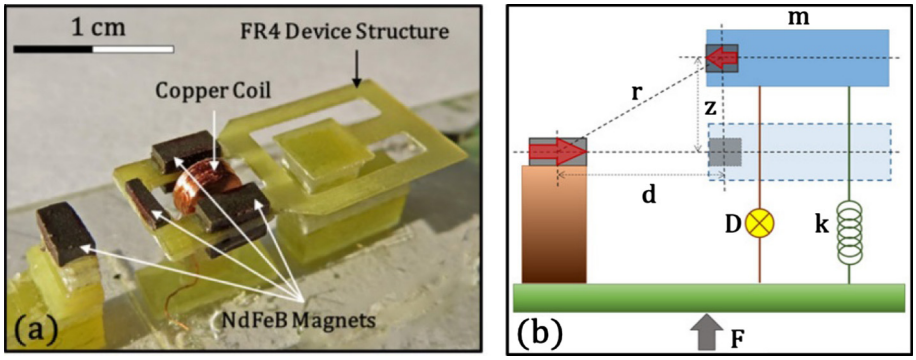


Fig. 8. (a) Fabricated bistable micro power generator developed by Podder et al. [68]. (b) Schematic representation of working mechanism of simple spring-mass system with repulsive magnets.

1 kΩ. More recently, in order to operate and tune the electromagnetic generator in a high frequency range, Mallick and Roy [69] also reported bidirectional FR4 based energy harvester using capacitive and inductive load. Four different spring configurations were discussed at different frequencies using laser micromachining technology. A maximum power of 468.17 μW, 348.2 μW, 4.31 μW, and 6.54 μW was obtained from prototype P1, P2, P3, and P4 at 58.6 Hz, 83.8 Hz, 162.9 Hz, and 42.9 Hz, respectively (see Fig. 9).

3.1.2. Using different shapes of cantilever

Besides using rectangular shaped cantilever, researchers also studied other shapes (e.g., T-shaped, U-shaped, S-shaped, spring type, etc.) of cantilever to investigate the efficiency improvement of the generator. Starting from 2000, Li et al. [70] researched ways to design, analyze, and experimentally test of VMPG having a size of ~1 cm^3. To optimize the size of the prototype, laser micro-machined spring was used as a resonator. A voltage quadrupler circuit was used for rectifying generated ac voltage into DC. The prototype can generate 10 μW and 2 V DC at 64 Hz with an amplitude of 100 μm. Similar to Li et al. [70], Ching et al. [71] fabricated a prototype with NdFeB to harvest power to drive the inferred transmitter at different vibration modes. It is observed that the voltage and power output of the prototype were 4.4 V_{p-p} and ~830 μW at a frequency range between 60 and 110 Hz with approximately 200 μm vibration amplitude.

A detailed description of design methodology and fabrication process of liner micro energy harvester was explained by Williams et al. [72]. Permanent magnet samarium–cobalt was attached to the flexible GaAs polyimide membrane. The developed prototype was tested in various environment conditions (e.g., air and vacuum). A maximum power of 0.3 μW was obtained at 4 MHz. In a subsequent research, similar spring type vibrator was fabricated by Wang et al. [73] using MEMS technique. ANSYS was used to determine the resonant frequency and different modes of the system. Permanent magnet NdFeB and two lair of copper coil were used for their prototype as shown in Fig 10(a). Their prototype

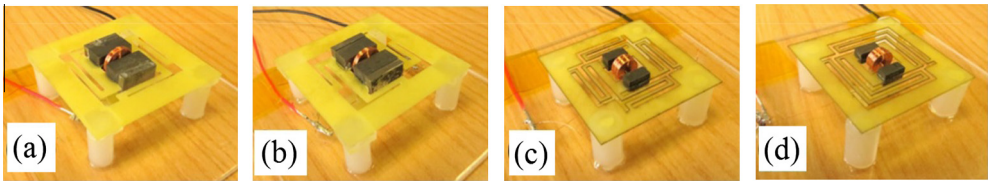


Fig. 9. (a)–(d) Four different spring configurations fabricated on FR4 developed by Mallick and Roy [69].

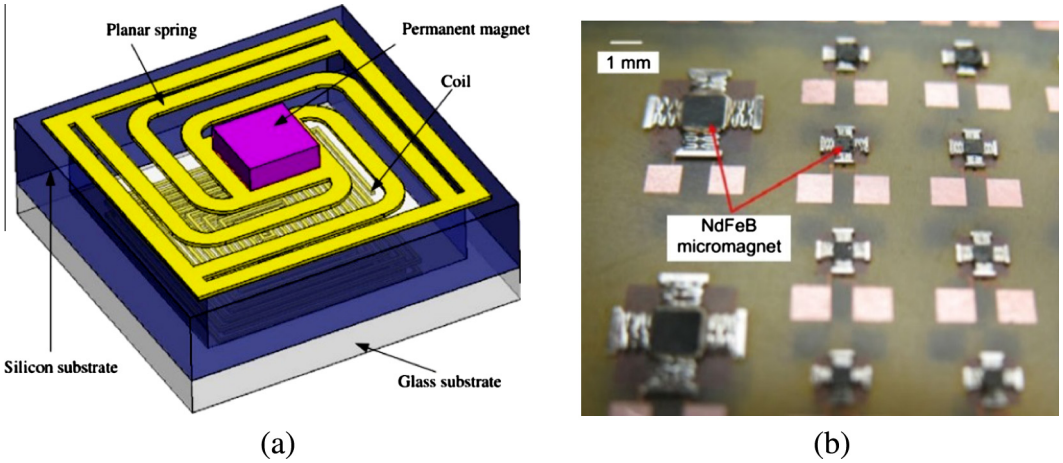


Fig. 10. (a) Schematic architecture and (b) fabricated electromagnetic generator developed by Wang et al. [73,74].

generates a maximum of 60 mV_{ac} at 121.25 Hz with 1.5 g acceleration. In a later study, Wang et al. [74] presented a fabrication process of micro power generator using resin-bonded NdFeB magnet powder. The magnet powder was used to make different sizes of magnet discs (see Fig. 10(b)) using micro patterning process.

Rather than using the copper spring type resonator, Lu and Hwang [75] used silicon helical micro-spring in their developed generator. Ferroplatinum permanent magnet membrane, copper coil, and two glass pieces were used to fabricate their prototype (see Fig. 11). A maximum voltage and power of 44.2 mV and 114.5 μW was measured at 60 Hz with a vibration amplitude of 0.03 mm. The output power becomes 4.2 times greater at 0.05 mm vibration amplitude than uncontrolled vibration amplitude.

Another novel approach to improve the efficiency of the micro electromagnetic energy harvester is to use three dimensional excitations at different modes with corresponding frequencies. Liu et al. [76] fabricated a novel power generator chip which consists of double layer three sets of aluminum coils, circular type spring with magnet, and supporting beam. Different modeling (e.g., mechanical, dynamic, and electro-mechanical modeling) and simulations were conducted to finalize the design of the prototype. Plasma-enhanced chemical vapor deposition (PECVD) technology was used to fabricate the energy harvester. The prototype generates 0.016 μW, 0.0087 μW, and 0.0045 μW at 1285 Hz, 1470 Hz, and 1550 Hz, respectively. In a later research, Liu et al. [77] minimized the distance between magnet and energy harvester chip to achieve better performance of the generator. Besides, Wang et al. [78] designed a flow induced electromagnetic VMPG. The vibration was induced from kármán vortex street which allows the magnet to move under the coil. The size of the harvester is 37.9 cm^3. Their fabricated energy harvester can generate 20 mV_{pp} and 1.77 μW at 62 Hz.

Arafa [79] used a trapezoidal plate energy harvester as shown in Fig. 12(a) for their developed VMPG prototype. Such trapezoidal plate design helps to obtain a close gap between two consecutive modal frequencies to achieve a wide bandwidth of the harvester. It was seen that the frequency ratio of mode I and II is 1.7 (19 Hz and 32 Hz). A dynamic model was described to anticipate the performance of the system using 30 Ω, 100 Ω, and 1000 Ω load resistance. El-Hebeary et al. [80] continued the research conducted by Arafa [79] by changing the geometry of the plate (see Fig. 12(b)) to widen the frequency bandwidth more. The modified geometry becomes V-shaped. It is noticed that their designed harvester can generate voltage at three different modes using three different resonance frequencies (e.g., 8 Hz, 11.8 Hz, and 19.2 Hz).

In a later study, Khan and Ahmed [81] developed a novel electromagnetic power generator having two permanent magnets with planar and wound coils. A latex membrane was placed between two magnets and coils were fabricated by PCB technology. Teflon spacers were used to create gap between magnets and coils. The dimension of the developed prototype is 18 × 18 × 18 mm^3. The open circuit voltage and load power are 15.7 mV and 11.05 mV, and 1.8 μW and 2.1 μW, respectively at a frequency range between

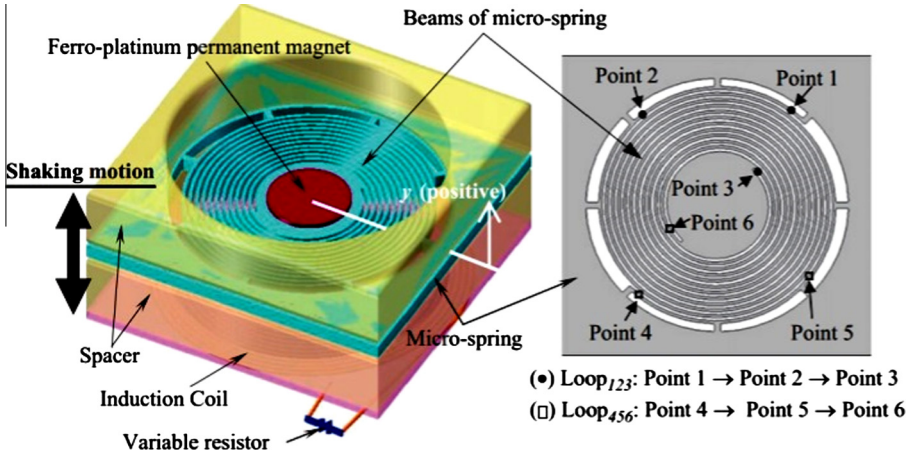


Fig. 11. Schematic representation of electromagnetic micro energy harvester designed by Lu and Hwang [75].

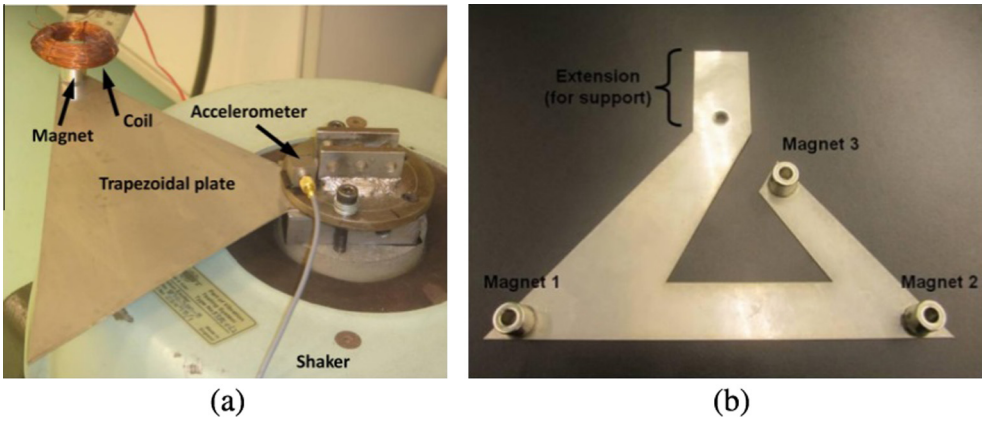


Fig. 12. V-shape multimodal energy harvester developed by (a) Arafa [79] and (b) El-Hebeary et al. [80].

10 and 80 Hz at 0.3 g acceleration. Besides, Khan et al. [82] developed similar electromagnetic power generator using PDMS membrane. Slotted polycarbonate plastic was used as a spacer instead of Teflon spacer. The modified size of the prototype was $15 \times 15 \times 10\ mm^3$ (see Fig. 13(a)). A maximum voltage and power of 88.8 mV and 39.4 μW was measured at 108.4 Hz under 0.1–3 g acceleration.

In a subsequent research, Yang et al. [83] used circular type elastic rod for their electromagnetic power generator to harvest energy at a wide frequency range. Ansoft Maxwell 3D was used to obtain the maximum performance of the prototype (see Fig. 13(b)). The prototype generates a maximum power of 13.4 mW at 5.7 Hz with an acceleration of 0.6 g.

3.1.3. Using cylinder shaped structure

Besides, using different shapes of cantilever (e.g., rectangular, spring type, V-shaped, circular rod, etc.), researchers also considered cylindrical shape structure for vibration based electromagnetic energy harvesters. Von Büren and Tröster [84] designed a tubular shaped VMPG using translational motion of the magnets. Translator bearing was also used in the generator architecture. In order to optimize the generator size, stator and translator parameter, load resistance, and resonant frequency were optimized. The size of the combined stator and translator is $0.25\ cm^3$ (see Fig. 14). The prototype can generate 2–25 μW based on different position of the human body.

Saha et al. [85] developed similar tubular type electromagnetic power generator for human usage. Their generator consists of 3 sets of oppositely polarized permanent magnets placed in a Teflon tube. Top and bottom magnets are fixed whereas the middle magnet moves vertically. 1000 turns of coil was used outside of the tube for electromagnetic induction purpose. The developed prototype has a maximum power 0.30 mW and 1.86 mW at 8 Hz with matched load (800 Ω). In a subsequent research, Foisal et al. [86] used similar magnet configuration to fabricate the electromagnetic energy harvester. Two different configurations with an array of four electromagnetic generators were developed. The total volume of prototype A and B were $108.11\ cm^3$ and $40.18\ cm^3$. A maximum power of 2. mW and 2.09 mW was measured at 7–10 Hz from prototype A and B, respectively. The power density of prototype B is found more than prototype A.

Munaz et al. [87] extended the research by Foisal et al. [86] using multi-pole magnets in their designed energy harvester. Similar cylindrical tube (acrylic glass), copper coil, and NdFeB were used to develop the generator. MATLAB was used to measure the open circuit voltage which was 6600 mV. Prototype can generate 4.84 mW at 6 Hz with an acceleration of 0.5 g. Similar battery type electromagnetic generator was proposed by Cepnik et al. [88]. A simple equation was derived to directly calculate the induced voltage and electromechanical damping of the electromagnetic vibration generator. The calculation takes 50% less time than conventional calculation system using their developed electromagnetic coupling equations and optimization method. Optimized

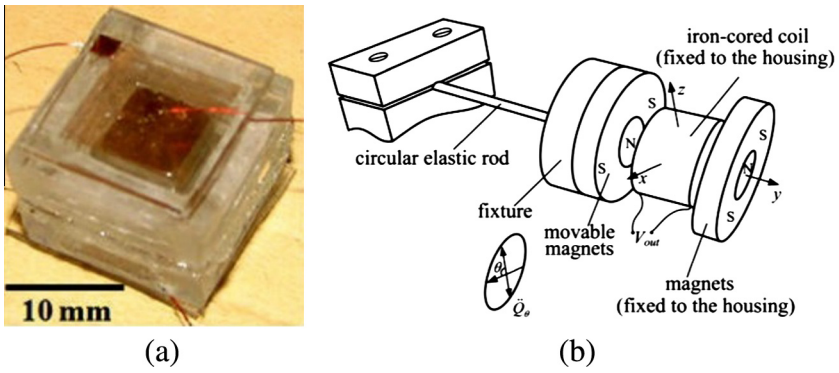


Fig. 13. (a) PDMS membrane type energy harvester developed by Khan et al. [82]. (b) Vibration based electromagnetic energy harvester using cylinder type rod developed by Yang et al. [83].

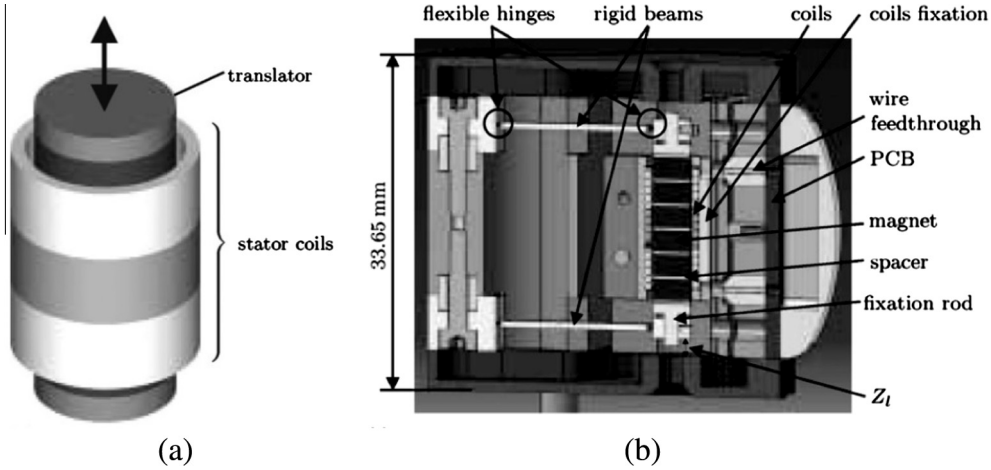


Fig. 14. (a) Schematic diagram of 3D model of tubular stator with translator ($0.25\ cm^3$). (b) Cross-sectional view of the generator [84].

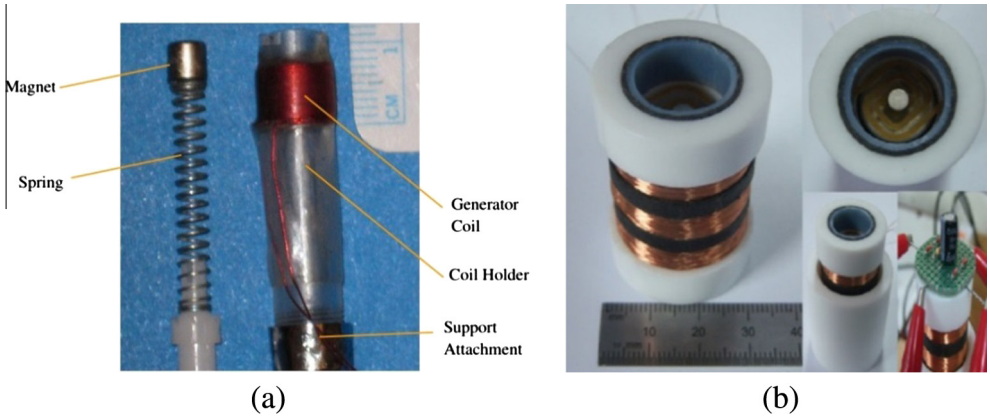


Fig. 15. (a) Magnet with spring and cylindrical structure with coil are the two parts of proposed electromagnetic vibration energy harvester [89]. (b) Prototype designed by Lee et al. [91]. NdFeB magnet was placed inside the Teflon tube between top and bottom FR4 springs. Copper coil was warped around the tube. A rectifier circuit was also attached to the top of the generator for AC–DC conversion.

prototype can generate an average power of 20.6 mW at 50 Hz with 1 g acceleration. In a later study, a novel approach to calculate the electromagnetic properties of the electromagnetic vibration power generator was presented by Elvin and Elvin [89]. Rare earth magnet i.e., neodymium was attached to a spring inside a tubular structure (see Fig. 15(a)). Two different coil configurations were used. First configuration was with one layer of copper coil with 23 turns and second one was with two layers. A normalized power of 1.7 mW/[$(m/s^2)^2$ cm^3] was obtained at 112.25 Hz.

Besides, a new approach of harvesting energy from low frequency and non-periodic vibration using Parametric Frequency-Increased Generator (PFIG) was presented by Galchev et al. [90]. PFIG has three magnetically tied structures. The internal displacement of the structure is fixed which allows it to oscillate at high frequency. The total size of the generator is 3.75 cm^3. The maximum power output of designed prototype is 163 μW at 10 Hz which can generate power up to 60 Hz. Lee et al. [91] also used spring (flame resistant (FR4)) inside the Teflon tube for moving the magnets in their proposed vibration generator. Two thin FR4 spring, NdFeB magnet, and copper coil were used to construct the prototype (see Fig. 15(b)). The bottom and top FR4 springs were used to decrease the stress on the springs and also to get a linear movement of the magnets. A maximum power of 1.52 mW was obtained at 16 Hz with 0.2 g acceleration. It was reported that their designed prototype can generate 2.4 mW from car engine.

Additionally, Delnavaz and Voix [92] developed an electromagnetic energy scavenger using human breath pressure. In order to use the breath, a breath mask was used with connecting tubes which was connected to the electromagnetic module. Copper coil was warped outside of the tube. Two magnets were placed: one at the top and another one at the bottom position of the tube. The third magnet moves between two magnets inside the tube which is surrounded by coil. The prototype can generate 25 mV and 3.1 μW. More recently, the research of Morgadoa et al. [93] focused on mathematical modeling of the cylindrical shape electromagnetic VMPG. The mathematical modeling is based on Newton's second law. However, a nonlinear mathematical expression has been used for the consequential magnetic force. It is reported that magnets size, gap between these magnets, number of coil windings are responsible to optimize the power generation of this cylindrical type electromagnetic energy harvesters.

3.1.4. Using power conditioning circuit

In order to improve the efficiency of the vibration based electromagnetic generator, different power management circuits were incorporated with prototype. Starting from 1998, Rajeevan and Chandrakasan [94] designed a self-powered digital signal processing electromagnetic transducer implemented by CMOS technology. Their designed chip consists of an ultra-low power controller and digital signal processing (DSP) load circuit. To construct a self-powered system, an integrated circuit which consists of a DC–DC converter and a FIR filter were introduced. The electromagnetic transducer can harvest 400 μW at 500 kHz.

In a later study, Hadas et al. [95] used a power management circuit in their designed power generator to rectify as well as stabilize the generated voltage. A maximum power voltage output of 3–6 μW and 2.5 V was measured at 34 Hz with amplitude of 50–150 μm. Schottky barrier diodes and 220 μF capacitor were used in the generator circuit for rectifying and stabilizing the purpose. Further research on power management circuit conducted by Dayal et al. [96] presented a micro power generator integrated with a single stage AC–DC boost converter. Single stage AC–DC boost converter was used for power processing of their prototype. A detailed description of numerical and experimental work was presented to verify the functionality of the designed system. The voltage output of the prototype is 0.45 V at 108 Hz.

More recently, Bowden et al. [97] researched ways to overcome the frequency limitation of the VMPG using electrical tuning method. A voltage-source-converter was used as an AC–DC boost converter for rectifying the generated power and a static converter was integrated for power factor correction. A full H-bridge circuit of MOSFET was used to run the full operation of the converters. Experimental results indicate that switch-mode converter used in the tuning circuit increases the −3 dB power bandwidth of the generator 3 times more than the untuned one. A summary of literature review on vibration based electromagnetic micro power generators has been listed in Table 4.

3.2. Piezoelectric VMPGs

Piezoelectric is another common transducer mechanism which has been used in VMPGs. Different piezoelectric materials (e.g., PZT, PVDF, AlN, etc.) with different structures were used to fabricate the VMPGs. A list of literature review has been presented in this subsection based on different materials and different geometry shapes.

3.2.1. Using different piezoelectric materials

Using footsteps of human beings, Kymissis et al. [45] presented three different configurations to convert vibration energy into electrical energy. Among them two are piezoelectric and one is electromagnetic in nature. PZT and PVDF were used in piezoelectric

Table 4
Summary of literature review of vibration based electromagnetic micro power generators.

Reference, year	Magnet	Size	Resonant frequency (Hz)	Amplitude	Power	Volt.	Load resistance (Ω)	Acceleration (g = 9.81 m s^{-2})
Williams and Yates [11], 1996		25 mm^3	70	50 μm	1 μW			
			330		0.1 mW			
Li et al. [70], 2000		1 cm^3	64	100 μm	10 μW	2 V		1.69 g
Willium et al. [72], 2001	Samarium–cobalt		4×10^6		0.3 μW		39	
El-hami et al. [47], 2001	NdFeB and samarium–cobalt	240 mm^3	322	25 μm	0.53 mW	14 mV	0.28	
Ching et al. [71], 2002	NdFeB	1 cm^3	60–110	200 μm	830 μW	4.4 V_{p-p}	1000	9.7 g
Mizuno and Chetwynd [49], 2003	NdFeB	500 × 100 × 20 mm^3	58,000	100 nm	6 nW	1.4 mV	82	
Glynne-Jones et al. [48], 2004	NdFeB	A: 0.84 cm^3	322	0.36 mm	37 μW		0.6	0.26 g
	NdFeB	B: 3.15 cm^3			157 μW			
Kulah and Najafi [50], 2004	NdFeB	400 × 30 × 10 μm^3	11,400		2.5 μW	150 mV		
Ṕerez-Rodŕıguez et al. [55], 2005	NdFeB		120		385 μW	0.5–0.9 V		0.25 g
Beeby et al. [51], 2005			6400	0.14 mm		0.38 V	77	0.196 g
Torah et al. [57], 2006	NdFeB	150 mm^3	56.6		17.8 μW	52 mV	150	60 mg
Spreemann et al. [56], 2006		1.5 cm^3	30–80	100 μm	0.4–3 mW		20	
Koukharenko et al. [52], 2006	NdFeB	100 mm^3	1615 & 9500	240 μm	0.11 & 3.35 mW	0.7 & 4.15 V	2000	0.4 g
Kulkarni et al. [53], 2006		30 mm^3	7500	240 μm	75 μW	55 mV	37.5	0.11 g
Beeby et al. [58], 2007			52		46 μW	428 mV	4000	60 mg
Hadas et al. [95], 2007	NdFeB	50 × 32 × 28 mm^3	34	50–150 μm	3–6 mW	2.5 V	1000	
Wang et al. [73], 2007	NdFeB	0.18 mm^3	121.25	738 μm		60 mV_{p-p}		1.5 g
Kulkarni et al. [54], 2008	A-NdFeB	106 mm^3	8080		148 nW		52,700	0.398 g
	B-NdFeB	106 mm^3	9840		23 nW		52	1 g
	C-NdFeB	150 mm^3	60	1.5 mm	586 nW	23.5 mV_{p-p}	110	0.9 g
Saha et al. [85], 2008		12.48 cm^3	8		0.3–2.46 mW		800	0.5 g
Sari et al. [59], 2008	NdFeB	14 × 12.5 × 8 mm^3	4200–5000	1 μm	0.4 μW	10 mV	250	
Sari et al. [3], 2009	NdFeB	9.5 × 8 × 6 mm^3	3400		56 pW/cantilever	0.67 mV	250	
Sari et al. [60], 2010	NdFeB	8.7 × 7 × 2.5 mm^3	70–150	0.44–2 mm	6.6 nW/cantilever	13.5 mV	150	
Solaiman et al. [61], 2010					190 μW	0.021 V	2	
Zhu et al. [15], 2010	NdFeB		67.6–98		61.6–156.6 μW			0.06 g
Lu and Hwang [75], 2011	Ferroplatinum		60	0.03 mm	114.5 μW	44.2 mV	10.6	0.45 g
Dayal et al. [96], 2011	NdFeB		108	2 mm		0.45 V		
Galchev et al. [90], 2011	NdFeB	3.75 cm^3	10		13.6 μW			1 g
Cepnik et al. [88], 2011			50	100 μm	20.6 mW			1 g
Wang et al. [78], 2012		37.9 cm^3	62		1.77 μW	20 mV		
Lee et al. [91], 2012	NdFeB		16		1.52 mW	4.8 V	5460	0.2 g
Foisal et al. [86], 2012	NdFeB	A: 108.11 cm^3	7–10		2.23 mW	3.326–5.770 V		0.5 g
		B: 40.18 cm^3			2.09 mW	3.596–5.437 V		
Delnavaz and Voix [92], 2012				40 mm	3.1 μW	20 mV	214	
Liu et al. [76], 2012	NdFeB	10 × 8 × 0.45 mm^3	1285		0.016 μW	3.6 mV	1800	1 g
Zorlu and Külah [62], 2013	NdFeB	2.5 ∗ 2.5 ∗ .5 mm^3	10	5 mm	18.5 nW	2.1 mV		1 g
Pashaei and Bahrami [64], 2013	NdFeB	0.64 cm^3	5900		46.6 μW	67.4 mV		
Liu et al. [77], 2013		0.035 cm^3	840		5.5 nW		626	1 g
			1070		0.5 nW			
			1490		4.1 nW			
Zorlu et al. [63], 2013		10.4 × 8.8 × 5 mm^3	10	3 mm	1.2 nW	6.94 mV		0.6 g
Munaz et al. [87], 2013	NdFeB (N35)	9.043 cm^3	6		4.84 mW	6600 mV	1000	0.5 g
Ooi and Gilbert [65], 2014	NdFeB (N35)		21.3			259.5 mV		0.08 g
Yang et al. [83], 2014			5.7		13.4 mW		110	0.6 g
Khan and Ahmad [81], 2014		18 × 18 × 18 mm^3	10–80		1.8 μW & 2.1 μW	15.7 & 11.05 mV		3 g
Khan et al. [82], 2014	NdFeB	15 × 15 × 10 mm^3	108.4		68 μW	48.5–88.8 mV		3 g
Podde et al. [68], 2014	NdFeB		35		22 μW	150 mV	1000	0.5 g
Sato and Igarashi [67], 2015	NdFeB		30		0.1 mW	>0.1 V	300	
Mallick and Roy [69], 2015	NdFeB	P1, P2–2.5 × 2.5 mm^2	P1-58.6		468.17 μW	1.06 V	2400	0.3 g
			P2-83.8		348.2 μW	0.89 V	2100	
		P3, P4 = 2.2 × 2.2 mm^2	P3-162.9		4.31 μW	0.058 V	780	
			P4-42.9		16.54 μW	0.122 V	900	

energy harvester. Piezoelectric harvester was identified more suitable than electromagnetic one. A peak power of 80 μW was measured at 1 Hz from piezoelectric harvester attached to the shoe. This generated power was transmitted through a radio frequency (RF) transmitter. Similar research was continued by Shenck and Paradiso [98] by using the same material and procedure. The prototype has a power of 1.3 mW and 8.4 mW at 0.9 Hz using PZT and PVDF, respectively. It was observed that electromechanical efficiency of the generator using PVDF is 0.5% and 20% with PZT generator. Additionally, a forward switching power conditioning circuit was designed and included with the harvester.

Similar material PZT was used by Glynne-Jones et al. [99] and White et al. [100] for developing their designed piezoelectric energy harvester based on thick film piezoelectric mechanism. A detailed fabrication process was illustrated using thick film piezoelectric technology. The developed piezoelectric generator can generate 3 μW at 80.1 Hz under 0.8 mm vibration amplitude [99] while the other similar generator can generate 2 μW under 09 mm amplitude at same frequency [100].

In a subsequent research, Roundy et al. [19], and Roundy and Wright [27] investigated the piezoelectric energy harvester performance using PZT bimorph on a cantilever beam. A literature review on low power generation using vibration was presented by Roundy et al. [19] and based on the literature, an experimental work was conducted. The developed generator has a power output of 250 μW at 120 Hz under 2.25 m s^{-2} acceleration. Furthermore, Roundy and Wright [27] conducted a similar research on modeling, design, and optimization using PZT-5H for the electrostatic generator. Their proposed electrostatic generator has two layers of bending elements. The size of their generator is 1 cm^3 with an output power of 375 μW at 120 Hz (see Fig. 16).

Rather than using general PZT for piezoelectric energy harvester, Lu et al. [101] used modified PZT-PIC255 and single crystal PZN-8%PT for developing their generator prototype. The experimental results showed that the power output varied at different load resistances at same frequency (2939.8 Hz). The optimum power output is 0.66 mW at 68 kΩ and 0.571 mW at 215 kΩ from PZT-PIC255 and PZN-8%PT, respectively. PZT-PIC255 is found sensitive to load resistance whereas PZN-8%PT is sensitive to resonance frequency. Besides, Bayrashev et al. [102] proposed a new technique for low frequency vibration based piezoelectric power generator using PZT with Terbium Dysprosium Iron alloy (Terfenol-D) as shown in Fig. 17(a). Terfenol-D is a good magnetostrictive element and it has a good electrical conductivity. PZT was placed between two Terfenol-D layers to increase the voltage generation. The results show that the power output varies from 10 to 80 μW at 1–30 Hz.

A complete mathematical model of the piezoelectric power generator model was presented by Sodano et al. [103] using PZT material. Quick pack model QP40N was used to validate the model. The QP40N consists of complex PZT layer and a beam. The model was tested at various mechanical conditions including damping effect. Another piezoelectric material AlN was used with PZT to fabricate the micro piezoelectric generator [104]. Marzencki et al. [104] presented detailed fabrication process of piezoelectric generator using AlN and SiO_2 with Si layers. It was reported that the prototype can generate 60 nW from AlN layer whereas using typical PZT it can generate 600 nW. In a subsequent study, the work is continued by Muralt et al. [105] who fabricated and tested a thin film piezoelectric micro power generator (see Fig. 17(b)). PZT was deposited on the thermal oxide layer ID electrode in fabrication steps. The voltage and power output are 1.6 V and 1.4 μW at 870 Hz under maximum load impedance.

In a later research, Jeon et al. [106] also described the fabrication process of thin film piezoelectric generator using three photo mask processes. Sol–gel-spin coated PZT with top Pt/Ti electrode was used to fabricate the device (see Fig. 18(a)). It was reported that their designed d_{33} mode generates more voltage than d_{31} mode. A maximum voltage and power of 2.4 V_{dc} and 1 μW was measured at 13.9 kHz across 5.2 MΩ resistance. The energy density

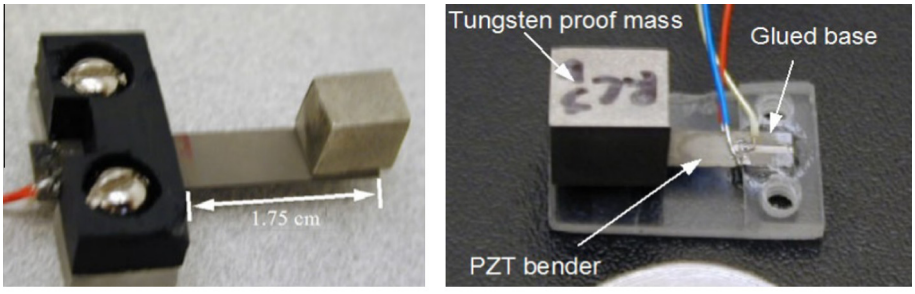


Fig. 16. (a) Designed prototype using two layer of PZT-5A and (b) optimized prototype (constraint length is 1.5 cm) developed by Roundy and Wright [27].

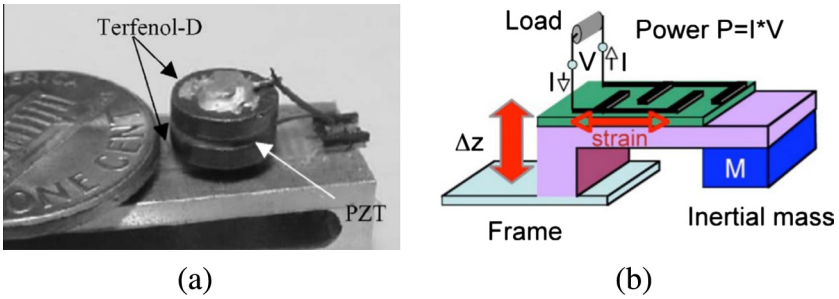


Fig. 17. (a) Developed piezoelectric generator using PZT with two Terfenol-D layers [102]. (b) Schematic presentation of fabricated thin film PZT energy harvester attached to the cantilever beam with tip mass [105]. The PZT film is 2 μm thin which is deposited on the SOI wafer.

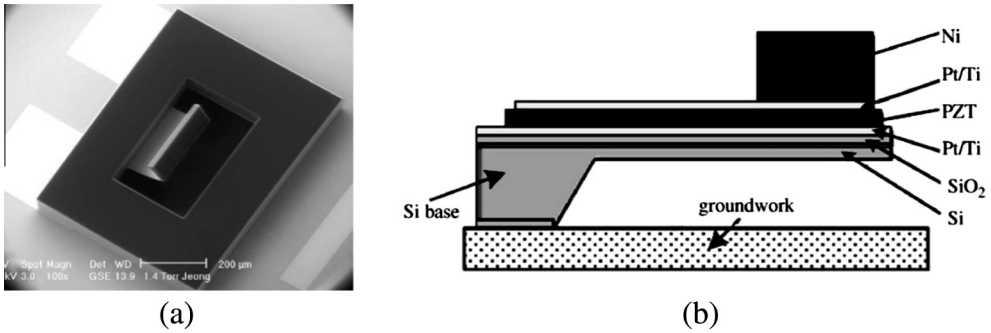


Fig. 18. (a) Fabricated piezoelectric thin film micro power generator. SiO_2 wafer, buffer layer of ZrO_2, PZT layer, seismic mass of SU-8, and Pi/Te electrode were used to fabricate the piezoelectric cantilever structure [106]. (b) Schematic diagram of cross sectional view of fabricated piezoelectric energy harvester [108].

of the developed prototype is 0.74 mW h/cm^2. Thin film Sol–gel-spin coated PZT was also used by Duggirala et al. [107] to fabricate the radioactive micro piezoelectric generator. Kinetic energy of radioactive β particle was stored as a mechanical energy in the piezoelectric materials. Then mechanical energy was transformed into electrical energy. The fabricated prototype can generate 1.13 μW at 38 Hz with a conversion efficiency of 37%.

Micromachining technology was used to fabricate the micro piezoelectric power generator using same Pi/Te electrodes with same Sol–gel coated PZT on silicon substrate by Fang et al. [108]. The developed prototype (see Fig. 18(b)) has a voltage and power output of 898 mV and 2.16 μW at 608 Hz across 21.4 kΩ load resistance. Leland and Wright [109] proposed a new approach (e.g., compressive axially preload) to harvest energy at low frequency from vibration. Such technique is used to compress the piezoelectric bimorph for making its resonance frequency lower. It was obtained that axial preload also increases the piezoelectric coupling coefficient. The designed generator can harvest 300–400 μW at a frequency range from 200 to 250 Hz. In order to tune the resonance frequency, Eichhorn et al. [110] also used the axial preload technique. It was reported that resonance frequency was tunable from 292 Hz to 380 Hz.

Additionally, Wu et al. [111] used frequency tuning mechanism by changing the positioning of the center of gravity of mass to adjust the resonance frequency of the generator. The results show that the developed prototype has a frequency range between 130 Hz and 180 Hz depending on the position of the mass. Besides, Challa et al. [112] also used frequency adjustment technique by introducing a novel approach of magnetic force technique. A prototype was developed and experimentally tested by using this magnetic force technique to adjust the frequency. It was reported that this technique allows tuning the resonant frequency to ±20% from untuned one. The results show that the prototype can generate 240–280 μW at a frequency range between 22 and 32 Hz. In another study, the frequency range varies from 3.19 to 12 Hz based on attractive magnetic force effect using PVDF material [113].

Aktakka et al. [114–116] further focused on the thinned film piezoelectric micro power generator on silicon substrate using batch mode, mask, and micromachining fabrication technology. Thinned PZT was deposited on SOI wafer with silicon mass. The results show that the designed prototype can generate 10.2 μW at 252 Hz under 2 g acceleration [115] and 205 μW at 154 Hz under 1.5 g [116]. Jambunathan et al. [117] focused on comparatively new fabrication technique (e.g., pulsed laser deposition (PLD)). The fabrication process includes top-down with deep reactive ion etching (DRIE). Different resonant frequencies with different size of the devices were tested to find out the optimum configuration. It was measured that fabricated prototype can generate maximum 51.4 μW at 615 Hz under 0.9 g acceleration. In order to make a micro or miniature device, which includes natural axis, resonant frequency, and load resistance, plays an important role, Leong et al. [118] investigated the mechanical and electrical design of the piezoelectric beam to fabricate a micro PZT energy harvester. It was reported that optimum deflection of the cantilever beam is important than stress. The developed prototype generates 4.5 μW and 960 mV at 80 kΩ under 10 m s^{-2} acceleration.

Kim et al. [119] researched ways to characterize the d_{31} and d_{33} modes of piezoelectric energy harvester and compare their output results. Interdigital electrode (IDE) was used to fabricate the d_{33} mode. The power output from d_{31} mode is 2.15 μW and 2.33 μW whereas from d_{33} mode it varies from 0.62 μW to 1.71 μW, depending on the size of the IDE, at 243 Hz. It was obtained that d_{33} with IDE has higher efficiency than d_{31} mode of PZT. Besides, Kim et al. [120] developed a dual PZT cantilevers with silicon mass using MEMS technology. Numerical analysis was carried out using finite element analysis with parametric analysis. The prototype generates a maximum voltage and power output of 118.5 mW and 0.34 μW at 78.7 Hz under 0.5 g acceleration. Another recently developed piezoelectric material is single crystal piezoelectric material $(1-x)$Pb(Mg1/3Nb2/3)O_{3-x}PbTiO_3(PMN-PT) which has a high piezoelectric and electromagnetic coupling coefficient. Tang et al. [121] also used d_{33} mode single crystal PMN-PZT with IDE. The fabricated thick film PZT energy harvester can generate 5.36 V_{P-P} and 7.182 μW at 406 Hz under the acceleration of 1.5 g.

A detailed analysis with experimental results has been conducted using different configurations (e.g., bi-stable single beam and magnetically coupled multiple beams) by different researchers. Trigona et al. [122] studied to compare different configurations using $PbTiO_3$ materials with NdFeB magnet at the tip of the cantilever. A maximum power output of ~5.5 μW was obtained at 450 Hz with 2.5 g excitation. Additionally, Cho et al. [123] investigated the relationship between control variables (e.g., material properties, geometry, and active and inactive layers) and structural performance of the generator. A detailed description of layers (see Fig. 19(a)) of the beam was discussed and mathematically presented. PZT: PSI-5A4E was used as a piezoelectric material to fabricate the prototype. The prototype can generate 52.5 mW at 30 Hz using 6.9 m s^{-2} excitation. More recently, Prušáková et al. [124] developed a piezoelectric energy harvester (see Fig. 19(b)) using zinc oxide (ZnO) as a sandwich between Al_2O_3 layers on Si substrate with RF and DC magnetron supporting technique. A maximum power and voltage of ~20 μW and 0.975 V was obtained from at ~595 Hz across ~10 kΩ.

Jaafar and Salleh [125] designed a novel piezoelectric power generator modifying the cantilever structure using silicon rubber on the tip of the beam. PSI-5H4E piezoelectric ceramic was used to develop the prototype. It was reported that adding extra rubber with the cantilever beam widens the frequency bandwidth by

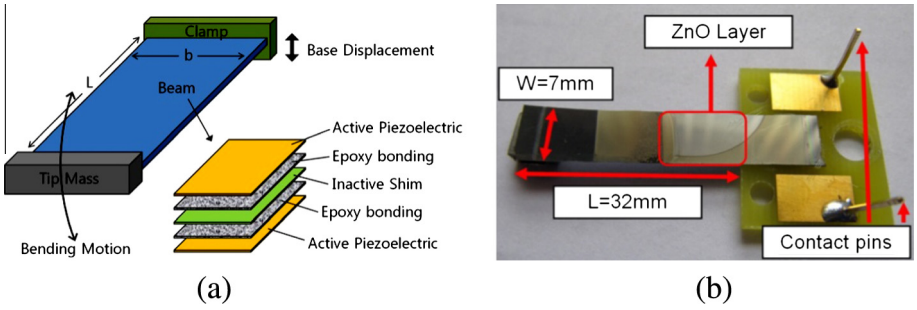


Fig. 19. (a) Schematic representation of different layers of a piezoelectric cantilever [123]. (b) Fabricated thin film piezoelectric micro power generator using ZnO layer on silicon substrate [124].

115%. The experimental results show that the prototype has a power output of 38.1 μW at 52 Hz across 110.3 kΩ load resistance.

3.2.2. Using different geometry of PZT cantilever beams

Deepak and Vikas [126] researched ways to improve the power output from vibration based piezoelectric energy harvester using different shapes (e.g., rectangular shape, U-shaped, T-shaped) of cantilever. ANSYS 10 was used to design the cantilever shapes in order to decrease the resonant frequency of the system. PZT-5A piezoelectric layer was used to design a unimorph having a size of $30 \times 10 \times 0.4$ mm^3. The designed cantilever has a voltage output of 2.7 V at 147 Hz. In a later research, using finite element analysis (FEA) in COMSOL multi-physics, Reddy and Kumar [127] also studied different shapes (e.g., rectangular, triangle, T, and π shaped) of cantilever to find out the sensitivity of the beams. It was reported that triangle shaped beam has a high sensitivity than other shapes of beam. It was obtained from the numerical simulation that displacement of triangular shaped beam is 9.7901×10^4 μm at 0.5 N/m^2 applied force.

Additionally, Basari et al. [128] suggested that triangular shaped PZT energy harvester is more efficient than normal rectangular PZT under matching impedance condition. It was stated that the efficiency of PZT generator depends on geometry of the cantilever beam, proof mass, matching impedance, and vibration force. Triangular PZT device has a regeneration efficiency of fixed 5% under changing load mass. Rather than using rectangular shape cantilever, Saadon and Sidek [129] designed an E-shaped cantilever to extract energy using piezoelectric vibration generator. Silicon

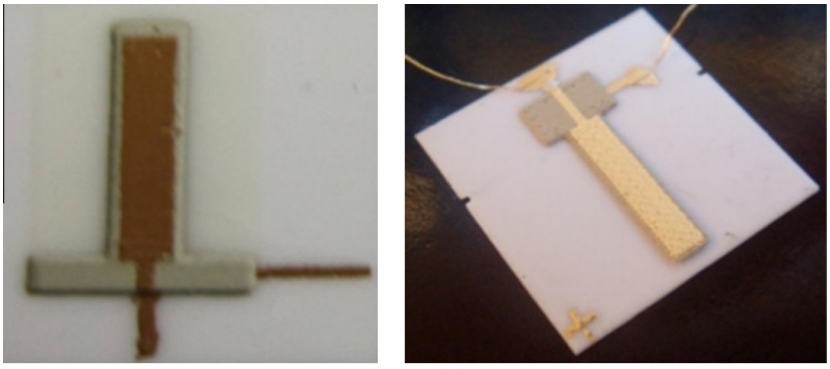


Fig. 20. Fabricated Au/PZT/Au piezoelectric cantilever using SrCO3-based sacrificial layer (a) before firing and (b) after firing [134].

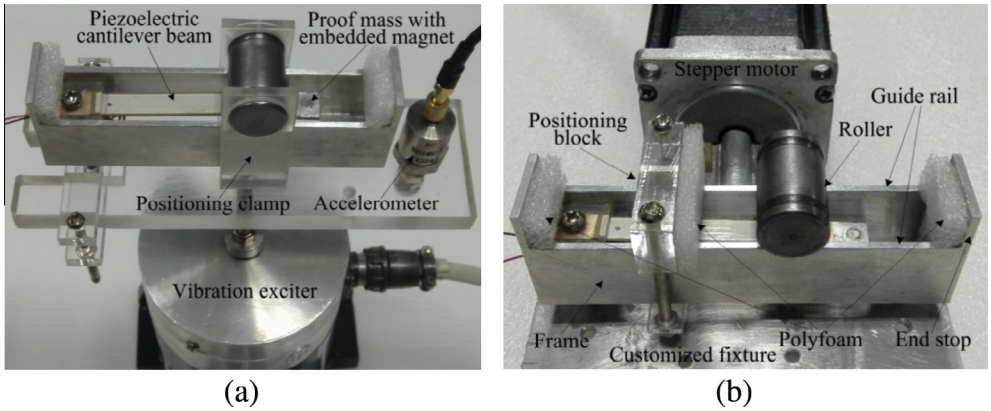


Fig. 21. Developed beam roller piezoelectric power generator prototype for (a) vibration and (b) sway experiment. The constructed beam was made of brass substrate and PZT-5H, single crystal chip. NdFeB magnet was attached to the free end of the beam [14].

and PZT were used to design the cantilever. The designed harvester generates 1 W at 2 kΩ resistive load under first mode resonant frequency of 15 Hz. Similar to the research conducted on E-shaped beam, Saadon and Sidek [130] presented a T-shaped beam for piezoelectric energy harvester. The designed prototype generates 2.4 μW at 11 Hz across 5 kΩ load resistance under 1 g acceleration.

In a subsequent study, Tufekcioglu and Dogan [131] described a parametric study of the design of piezoelectric energy harvester (PEH) and effect of stacking on the device performance. Cymbals with single-layer (C-PZT1) and two-layer-stacked (C-PZT2) disks were used as transducers to develop PEH. A maximum power of 141.61 μW and 104.04 μW were obtained at 153 Hz and 166 Hz across 40 kΩ and 80 kΩ from C-PZT2 transducer (BPZT-2) and C-PZT1 transducer (BPZT-1), respectively. After experiment it was obtained that stacked PZT generator harvests more energy than single layer C-PZT1 transducer. Ali et al. [132] focused on fabricating a micro piezoelectric power generator using silicon micromachining technology. AlN was used as a piezoelectric material between the top and bottom electrode. Four Schottky diodes were used in the external driving circuit to rectify the generated voltage. A maximum power output of 34.78 μW was measured at 572 Hz under 2 g acceleration.

Besides using PVDF material, Wen et al. [133] designed and tested a spiral shaped cantilever for harvesting energy at low frequency. In order to decrease the resonant frequency, cantilever length was increased and two different proof masses (e.g., silicon and copper) were used on both ends. The developed prototype has a voltage and power output of 1.8 V_p and 8.1 nW at 0.2 g acceleration across 100 MΩ load resistance. More recently, using screen print technology, Debéda et al. [134] demonstrated a piezoelectric thick film sacrificial layer process. A bridge of gold (Au), PZT, and (Au/PZT/Au) was fabricated using screen print method as shown in Fig 20. It was noted that the printed piezoelectric harvester is more suitable at higher frequency with in-plane d_{31} mode.

In order to widen the frequency band of the piezoelectric power generator, Zhang et al. [135] designed a cylindrical shaped nonlinear power generator using magnet levitation. Four doubled piezoelectric layers were used to develop the structure of the generator where the top and bottom magnets were fixed but the middle one was movable along the tube. It was obtained that the designed prototype has a frequency range from 0.1 to 30 Hz. More recently, Fan et al. [14] developed a beam-roller piezoelectric power generator which can harvest energy from multimode vibration (e.g., sway and bi-directional vibration). Frequency up-conversion technique was also used to operate the system in a wide frequency range. A maximum open circuit voltage output of 13 V was obtained at resonant frequency 32 Hz from *z*-direct vibration of the prototype (see Fig. 21). A summary of literature review on piezoelectric transducer based micro energy harvesters has been presented in Table 5.

3.3. Hybrid VMPGs

Recently, there is an increasing trend of using hybrid energy sources to improve the energy production from single generator system. Different combinations of energy sources especially

Table 5
Summary of literature review of piezoelectric VMPGs.

Reference, year	Material	Resonant frequency (Hz)	Power	Voltage	Load resistance	Acceleration (g = 9.81 m s^{-2}) (g)
Kymissis et al. [45], 1998	PZT, PVDF	1	80 μW	150 V_p	10 Ω	
Shenk [46], 2001	PZT & PVDF	0.9	1.3 mW & 8.4 mW		250 & 500 kΩ	
Glynne-Jones et al. [99], 2001	PZT-5H	80.1	3 μW		333 kΩ	
White et al. [100], 2001	PZT-5H	80	2 μW	1.2 V	333 kΩ	
Roundy et al. [19], 2003	PZT & PVDF	120	252 μW			0.25
Bayrashev et al. [102], 2004	PZT	5	10–80 μW	>1 V_{p-p}		
Lu et al. [101], 2004	PZT-PIC255 & PZN-8% PT	2939	0.66 mW & 0.571 mW		68 kΩ & 215 kΩ	
Roundy and Wright [27], 2004	PZT-5A	120	375 μW			0.25
Marzencki et al. [104], 2005	PZT/AlN	900	0.6 μW			1.02
Jeon et al. [106], 2005	Sol–gel-spin coated PZT	13,900	1 μW	2.4 V_{dc}	5.2 MΩ	
Duggirala et al. [107], 2006	PZT, radioactive thin film	38	1.13 μW	350 mV	90 kΩ	
Leland and Wright [109], 2006	Brass center shim coated PZT	200–250	300–400 μW			1
Fang et al. [108], 2006	Sol–gel coated PZT	608	2.16 μW	0.89 V	21.4 kΩ	
Challa et al. [112], 2008		22–32	240–280 μW		26 kΩ	0.082
Muralt, et al. [105], 2009	Thin film PZT	870	1.4 μW	1.6 V		2
Aktakka et al. [115], 2010	Thinned PZT	252	10.2 μW			2
Aktakka et al. [116], 2011	Thinned PZT-5A	154	205 μW			1.5
Jambunathan et al. [117], 2012	PLD- PZT	615	51 μW			0.93
Leong et al. [118], 2012	PZT		4.5 μW	960 mV	80 kΩ	1.02
Deepak and Vikas [126], 2013	PZT-5A	147		2.7 V		
Kim et al. [119], 2013	PZT-31 & 33 mode	243	2.5 μW & 062–1.71 μW			1.02
Saadon and Sidek [129], 2013	Si & PZT	15	1 W 0.25 mW-simulated	0.1 V_{pp} 0.45 V-simulated	2 kΩ 5 kΩ-simulated	0.1
Kim et al. [120], 2013	PZT-31 mode	78.7	0.34 μW	118.5 mV		0.5
Tang et al. [121], 2014	Single crystal PMN-PZT	406	7.182 μW	5.36 V_{p-p}		1.5
Trigona et al. [122], 2014	PZT-$PbTiO_3$	450	~5.5 μW			2.5
Cho et al. [123] , 2014	PZT: PSI-5A4E	30	52.5 mW			0.7
Wen et al. [133], 2014	PVDF	15–50	8.1 nW	1.8 V_p	100 MΩ	0.2
Tufekcioglu and Dogan [131], 2014	PZT-5H	153 166	C-PZT-2:141.61 μW C-PZT-1:104.04 μW	2380 mV 2885 mV	40 kΩ 80 kΩ	2
Saadon and Sidek [130], 2014	PZT	11	2.4 μW	0.12 V	5 kΩ	1
Ali et al. [132], 2014	AlN	572	34.78 μW		495 kΩ	2
Prušáková et al. [124], 2015	Thin-film ZnO	595	~20 μW	0.98 V	~10 kΩ	
Jaafar and Salleh [125], 2015	PZT: PSI-5A4E	52	38.1 μW	1.02 V	110.3 kΩ	0.25

electromagnetic and piezoelectric, and electromagnetic and thermoelectric are being widely used to optimize the efficiency.

A detailed explanation of theoretical and experimental work of hybrid vibration power generator consists of electromagnetic and piezoelectric transducer mechanism was presented by Tadesse et al. [136]. $Pb(Zn_{1/3}Nb_{2/3})O_3$–$PbTiO_3$(PZN-PT) single crystals was used as a piezoelectric plate (d_{31} mode) on the cantilever beam with magnet. The size of their designed prototype is $25 \times 30 \times 125$ mm^3 as shown in Fig. 22(a). It was reported that electromagnetic transducer is suitable for low frequency whereas piezoelectric is fit for high frequency. The power output from electromagnetic piezoelectric systems is 0.25 W and 0.25 mW, respectively at 20 Hz with an acceleration of 35 g. In a later study, Sang et al. [137] also designed a hybrid power generator using piezoelectric and electromagnetic energy conversion system. An analytical model was developed and experimentally tested in order to study the nonlinear behavior of the vibration and performance of the system. The voltage and power output of the prototype (see Fig. 22(b)) were 0.71 V and 10.7 mW, respectively at 50 Hz with a load resistance of 50 Ω. It was stated that hybrid generator can harvest 81.4% more power than an individual generator.

More recently, Li et al. [138] studied ways to harvest power effectively from multi-source (e.g., electromagnetic and piezoelectric system) power generator using wide random vibration (see Fig. 23(a)). The study includes modeling, simulation, experimental tests. Dimensionless parameters were developed for calculating the mean power and spectral density to make the system more effective in random excitation. It was reported that maximum power can be achieved when load resistance of the hybrid system becomes equal to the matching impedance at resonant frequency. It was also observed that coupling strength greatly affects the frequency band width (e.g., if the coupling strength becomes high then the frequency bandwidth becomes wide as well as mean power and power density of the system).

Additionally, Yu et al. [139] researched ways to improve the efficiency of the hybrid (e.g., piezoelectric and electromagnetic) power generator using a power conditioning circuit. MEMS piezoelectric cantilever with Si proof mass and NdFeB were used to build the hybrid power generator. PCB technology was used for micromachining the coil fabrication on the bottom surface of the harvester. PCB consists of AC–DC rectifier with DC–DC buck converter to regulate the generated voltage. The maximum voltage and power of 3.6 V and 40.62 μW was obtained at 55.9 Hz from the designed prototype (see Fig. 23(b)).

Another effective approach to generate power from the combination of thermoelectric and electromagnetic energy harvester was presented by Töreyin et al. [140]. Thermoelectric materials Cr–Al and magnet NdFeB were used in the cantilever based hybrid power generator. Ambient temperature was used as a heat source for thermoelectric module. The dimension of their designed prototype is $9.5 \times 8 \times 6$ mm^3. A maximum voltage and power of 16.7 mV and 1.91 nW (from thermoelectric 0.79 nW and electromagnetic 1.12 nW) was measured, respectively at 3.45 kHz (see Fig. 24).

Zhang et al. [141] studied a new vibration based hybrid generator combined with triboelectric nano-generator (TG) and an electromagnetic generator. TG is a new technology which converts low frequency vibration into electrical energy. The conversion principal of this generator is based on the combination of triboelectrification and electrostatic induction mechanism. The size of the hybrid generator is $5 \times 5 \times 25$ cm^3. The maximum power output from triboelectric nano-generator and an electromagnetic generator are 4.9 mW and 3.5 mW under 6 MΩ and 2 kΩ, respectively.

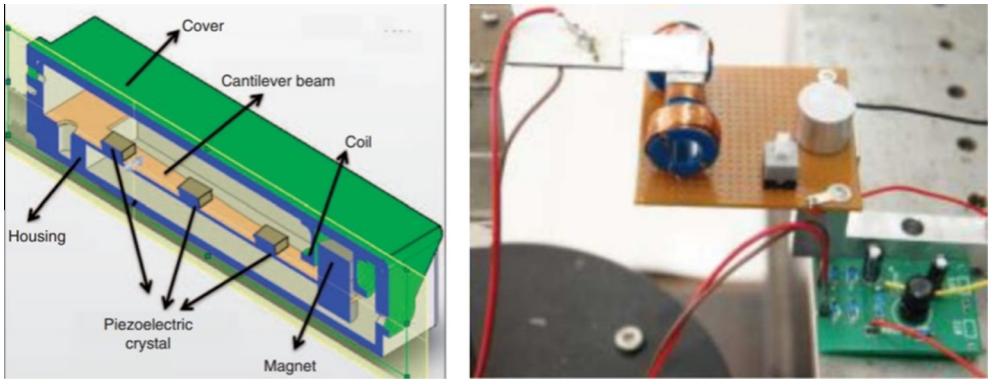


Fig. 22. (a) Schematic presentation of cross sectional view multimodal energy harvester (electromagnetic with piezoelectric system). T shape cantilever was used as a resonator [136]. (b) Hybrid power generator prototype combined with piezoelectric and electromagnetic system. Two piezoelectric plates were used with the cantilever substrate. A bridge rectifier circuit was used to convert the generated ac signal to dc [137].

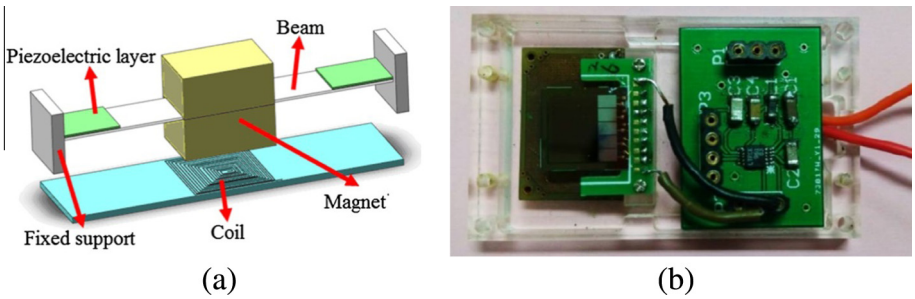


Fig. 23. (a) Schematic illustration of hybrid power generator [138]. (b) Developed hybrid power generator with power management circuit. Number of cantilever is 5 having a size of $5 \times 2.4 \times 0.05$ mm^3 [139].

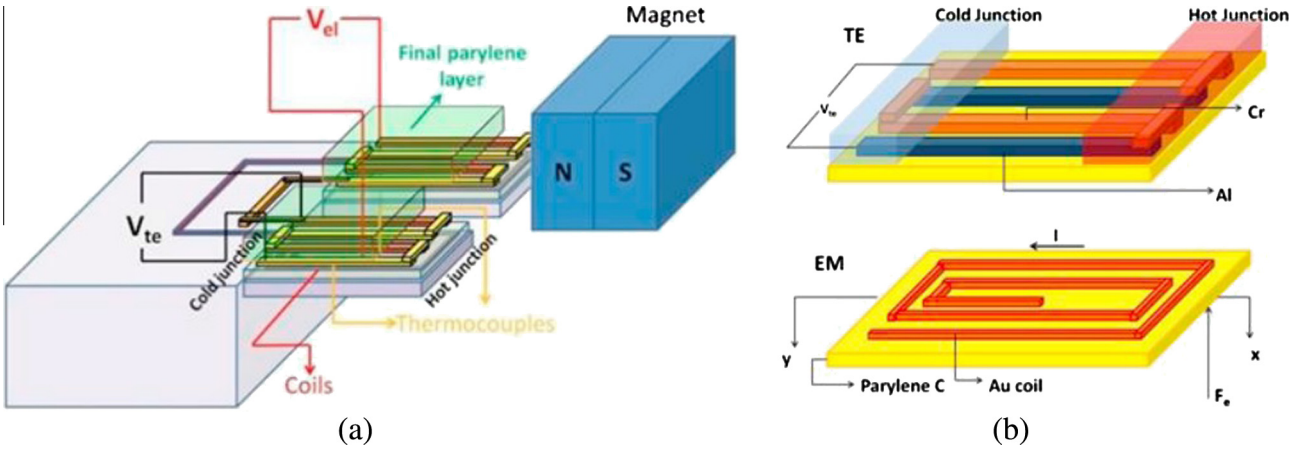


Fig. 24. (a) Schematic diagram of multi-source vibration based micro power generator. (b) Paylene-C was use for cantilever structure and Si was used as a heat sink for thermoelectric module [140].

Table 6
Summary of literature review of vibration based hybrid power generator.

Reference, year	Mechanism	Materials	Resonant frequency (Hz)	Power	Voltage	Load resistance (Ω)	Acceleration (g = 9.81 m s^{-2}) (g)
Tadesse et al. [136], 2009	Piezoelectric & Electromagnetic	PZN (PT)	20	0.25 W & 0.25 mW		120	35
Töreyin et al. [140], 2010	Thermoelectric & Electromagnetic	Cr/Al & NdFeB	3450	1.91 nW	16.7 mV	680	
Sang et al. [137], 2012	Piezoelectric & Electromagnetic	PZT-51 & NdFeB	50	10.7 mW	0.71 V	50	0.4
Yu et al. [139], 2015	Piezoelectric & Electromagnetic	PZT & NdFeB	55.9	40.62 μW	3.6 V		0.2
Zhang et al. [141], 2015	Triboelectric nano-generator & Electromagnetic			4.9 mW & 3.5 mW			

A summary of literature review on hybrid micro energy harvesters is given in Table 6.

4. Conclusion

Significant development of MEMS has made the micro power generators more demandable in the area of WSNs in recent years. Vibration based MPGs can be one of the best fits for the self-powered WSNs. This review paper presents the research headway of VMPGs. VMPG systems (i.e., electromagnetic, piezoelectric, and hybrid system) require external vibration sources to operate. However, vibration produced by real life sources is typically intermittent in nature which restricts harvesting power at constant rate using VMPGs. Nevertheless, due to the wide range of application potential and several inherent advantages, VMPGs can be suitable alternatives to fulfill the energy requirement at many small scale applications.

From the research conducted on VMPGs, it is noted that researchers have been facing some challenges to achieve required energy from the system. According to Eq. (1), the maximum power depends on vibration frequency (where natural frequency (ω_n) equals the system's vibrational frequency (ω_e)) and maximum amplitude (Y_{max}) of the external vibration force. It is known that the frequency of the environmental vibration is not predetermined as well as not stable which is low in amplitude and random. Therefore, this is hard to extract energy from such environment with VMPGs. But due to small size of the devices, the resonant frequency is so high that is difficult to achieve [11]. Another problem is the narrow operating bandwidth [142–144]. In most of the research papers, rectangular shaped cantilevers were used in piezoelectric or electromagnetic type VMPG because of their simple design, easy constructor or ease of fabrication. But the main disadvantage of using such shape is that it has a very poor average strain [130]. Low power density is (power/volume^3) another big problem of this shape. Many MPGs have been designed and built but most of them suffer low power density problem. Because of many challenges and limitation, there are more areas where improvements are necessary to make the VMPGs efficient and more usable. Such improvements may be in: developing new design and cantilever structure, improving strain by maximizing the proof mass, developing tuning circuit for achieve the resonant frequency, designing a wide bandwidth generator, implementing frequency up conversion technique, applying nonlinear dynamical systems, and improving piezoelectric material properties [145].

Therefore, a large portion of the recent research has been conducted to modify the generator size, shape, and to introduce power conditioning circuit in order to widen the frequency bandwidth system. Further research of such vibration based MPGs will accelerate the development of MEMS based energy harvester from renewable resources and make the miniature electric devices more reliable.

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